Waves and Devices Chapter of IEEE Phoenix

Rotor Blade Modulation

November 19, 2014

Ron Lavin
Assoc. Technical Fellow
The Boeing Company
Mesa, Arizona
ronald.o.lavin@boeing.com
Contents

• Introduction to Rotor Blade Modulation (RBM)
  – RBM Effects on Antennas
  – Representation Conventions
  – Quasi-Stationary Analysis
  – Doppler Bandwidth and Angular Sampling

• RBM Examples
  – Example #1: RBM of HF Towel Bar On Helicopter
  – Example #2: RBM of VHF Blade On Helicopter
  – Example #3: Wiper Modulation of FM Windshield Antenna
  – Example #4: RBM of UHF Satcom On Helicopter
  – Example #5: RBM of GPS On Helicopter
  – Example #6: RBM of Ku Band Satcom

• Mitigation Strategies

• Further Reading
Rotor Blade Modulation (RBM)

**Definition:** Rotor blade modulation (also called rotor modulation) is the degradation of the communication channel due to rotating rotor blades. Rotor blade modulation can involve many variables:

1. Frequency and polarization of the victim signal
2. Observation angle about the helicopter
3. Type and element radiation pattern of the antenna
4. Antenna mounting location
5. Helicopter airframe geometry
6. Aircraft attitude and flight mode
7. Blade geometry, e.g. the chord, length, shape, composition, and # of blades
8. Complex motions of the rotor blades (pitch, tilt, coning, flapping, etc.)
Effects on Communications

(1) Periodic scattering and blockages of radiation resulting in pattern distortion
(2) Modulation of input impedance
(3) Periodic depolarization of radiation resulting in pattern distortion
(4) Doppler effects

Important considerations are rotor blade width (W), wavelength (λ), proximity to the antenna, and relative orientation

- When λ << W and not in near field, simple blockage model works
- When λ >> W and not in near field, we can use simple wire model of blade In coupling model for direct far field calculation
- For λ/W ≈ 1 (or in near field or when in doubt) use full wave code to capture all interactions
Common Representations

RF Frequency
- Modulation level ($G_1$)
- Modulation level ($G_2$)
- Maximum gain ($G_{max}$)

Rotor Position
- Frequency (MHz)
- Rotation angle (degrees)

3D Modulation
- Modulation Level

Pitch Plane
- Pitch-Plane Rotor Modulation

Yaw Plane
- Yaw-Plane Rotor Modulation

Roll Plane
- Roll-Plane Rotor Modulation

Doppler Spectrum
- Frequency (Hz)
- Doppler Spectrum (dB)

© 2014 The Boeing Company
Quasi-Stationary Analysis

• Jean Van Bladel’s 1976 IEEE paper *Electromagnetic Fields in the Presence of Rotating Bodies* introduced the “quasi-stationary” analysis technique.

• In “quasi-stationary” analysis, each rotor position is treated as a separate, independent “snapshot”. Relativistic effects are ignored with this approach, as rotor blade speeds are far below the speed of light.

• Modern computational electromagnetic modeling tools such as CST® Microwave Studio® enable quasi-stationary analysis to be performed quickly and conveniently through parameter sweeps of rotor positions.
Recovery of Doppler

- Where Doppler frequency shifts matter (such as with DS/SS or FH/FM waveforms), a Doppler analysis must be included.

- Recovery of Doppler from quasi-stationary snapshots of gain involves a straightforward Fast Fourier Transform on Gain\( (\text{time}) \) to obtain Gain\( (\text{Frequency}) \).

- The number of snapshot rotor positions must be sufficient for the frequency of interest.

- Determining this requires we know the Doppler bandwidth.
Doppler Bandwidth Calculation

• The maximum Doppler frequency is $R \omega_r / \lambda$, where:
  – $R$ is ½ the tip-to-tip length of the rotor blade
  – $\omega_r$ is the angular rotor velocity
  – $\lambda$ is the carrier wavelength.

• The Doppler spectrum of magnitude and phase is a collection of frequency components residing at $\omega \pm n \omega_0$, where:
  – $\omega$ is the operating frequency of the antenna
  – $N_b$ is the number of blades
  – $\omega_0$ is the fundamental angular velocity $N_b \omega_r$
  – $n$ is an integer between 0 and $N-1$ inclusive
  – $\omega_r$ is the angular rotor velocity (assumed to be constant)
  – $N$ is the number of samples per period.
Example: Calculate the required number of position samples for the rotor blades for 5 kHz for a 4 rotor blade system that spins at 4.86 cycles per second.

\[ Doppler\ BW = n\omega_0, \text{ where } 0 < n < N \]
\[ = n \times 122.15 \text{ radians/second} \times 1 \text{ cycle/}2\pi \text{ radians} \]

Solving for \( n = N-1 \) using 5 kHz for Doppler BW:

\[ BW = (N-1) \times 122.15 / (2\pi) \]

\[ N = (2\pi) \times (5000+122.15) / 122.15 \]
\[ = 258.06 \text{ samples per 360 degrees} = .71683 \]

The required angular blade position sampling is about every .7 degree.
For the same system in the previous example, the table shows the blade position samples and angular sample spacing required for the maximum Doppler bandwidths for a few frequencies.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Max Doppler BW (Hz)</th>
<th>Required Samples per 360 degree Rotor cycle</th>
<th>Sample Spacing (Degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 MHz</td>
<td>1.1842</td>
<td>6.3408</td>
<td>56.7744</td>
</tr>
<tr>
<td>100 MHz</td>
<td>11.8422</td>
<td>6.8888</td>
<td>52.2585</td>
</tr>
<tr>
<td>1000 MHz</td>
<td>118.4222</td>
<td>12.36834</td>
<td>29.1065</td>
</tr>
<tr>
<td>10 GHz</td>
<td>1184.2224</td>
<td>67.1635</td>
<td>5.3601</td>
</tr>
<tr>
<td>40 GHz</td>
<td>4736.8896</td>
<td>249.8139</td>
<td>1.4410</td>
</tr>
</tbody>
</table>
Rotor blade interference is periodic and alters the amplitude, phase, or frequency of the desired signal.

Amplitude effects tend to be the most severe, and waveforms dependent upon amplitude modulation (e.g. VHF-AM) are the most severely affected.

Phase modulation and frequency modulation waveforms are also affected by Doppler effects of the moving rotor, multipath interference.

The next several examples illustrate the effects at different wavelengths for practical applications.
HF Rotor Modulation

- Most severe type of RBM
- Blades are resonant with wavelength
- Blades are in near field at HF
- Tip: Know your helicopter blades’ $\frac{1}{2} \lambda$ resonant frequency.
- This frequency will usually give maximum RBM.
HF Input Impedance

• Severe modulation of antenna Input Impedance

• A Smith Chart plot (not shown) reveals the modulation affects both radiation resistance and reactance.

• Therefore reactive tuning alone will not eliminate this effect.
HF Surface Currents

- Currents on antenna and airframe vary widely with blade position.
- Note the variability of the magnitude of the currents on the blades.
HF Patterns

- Severe pattern distortions and introduction of geometry and wavelength specific nulls and lobes

- The effects are due to alteration of radiating currents on the airframe and blades creating widely differing patterns

- This is not seen at much higher frequencies where pattern distortion is due mainly to far field scattering.
• Less severe modulation of antenna input impedance than HF.

• Note the input impedance differences are narrowband.

• This shows the frequencies at which the blade resonates.

• The radiated energy couples back to the antenna and returns to the source as an input reflection.
• Rotor modulation decreases with frequency
• Worst rotor modulation is under 100 MHz
• Doppler shift is not significant
Several years ago, windshield antennas were popular on cars for AM/FM radio reception.

Wiper blades can periodically interfere with windshield antennas.

Composition of blades matters.
FM Patterns and Input Impedance

• Modulation of Antenna Input impedance is significant.

• Pattern distortion is significant and due to antenna to blade coupling, resulting in periodic alteration of currents on the antenna.
Performance is shown for a rubber wiper blade.

Note a slight change in input impedance but virtually no pattern change.

For rubber, $\varepsilon_r = 3$. 
UHF Rotor Modulation

• A UHF satellite communication antenna is shown at right which requires field of view through the rotor blades.

• At UHF, far field effects dominate. UHF wavelengths are large compared to blade width, so diffractions help reduce periodic blockages.

• Rotor modulation of input impedance at UHF is significant.
UHF Patterns

- UHF wavelengths are large compared to blade width, so diffractions help reduce periodic blockages.

- The diffractions construct and destruct in the far field due to phase differences.
GPS Rotor Modulation

- L Band wavelengths, such as GPS signals, are near blade width.
- Diffractions help reduce periodic blockages but blockages are the dominant effect.
- Input impedance effects are diminished.

Two GPS Antennas: Forward and Aft
Tail Rotor RPM = 4 x Main Rotor RPM

Farfield Source [ffs1] Gain Right Polarisation (Phi=90)
GPS Patterns

Forward GPS Under Main Rotor

Aft GPS By Tail Rotor
Ku Band Rotor Modulation

• Shown at right is a Ku band satellite communications antenna with field of view through the rotor blades.

• Ku Band wavelengths are smaller than the blade width.

• Periodic blockages are the dominant effect.
Ku Patterns

Gain (IEEE), Phi=90 Port 1

Rotation=22.5
Rotation=11.25
Rotation=0
Rotation=67.5
Rotation=45
Rotation=33.75
Rotation=56.25
Rotation=78.75

© 2014 The Boeing Company
RBM Mitigation Strategies

1. Adding link margin helps especially at lower frequencies.

2. Increase physical separation between source antenna and rotor blades

3. Antenna diversity can help mitigate rotor modulation – choose asymmetrical locations.

4. Polarization diversity can help mitigate rotor modulation – use circular polarized elements, or use separate cross polarized elements.
5. Techniques used in commercially available through-the-rotor modems include fast rate automatic gain control signal conditioners to provide high rate gain boost to rotor-modulated signals, tuned or modified protocol layers which provide bursty transmissions, are tolerant of packet drops, and use tuned sliding window protocols.

6. Doppler spectrum issues may be encountered. This is more important for satcom and other extremely high frequency/ high data rate systems using variants of frequency or phase modulations, and it is difficult to alleviate these problems without advanced signal processing algorithms.
## Further Reading (1)

<table>
<thead>
<tr>
<th>Title</th>
<th>Author</th>
<th>Publisher</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>An Analysis of Helicopter Rotor Modulation Interference</td>
<td>Ivan Kedar</td>
<td>IEEE</td>
<td>1973</td>
</tr>
<tr>
<td>Electromagnetic Fields in the Presence of Rotating Bodies</td>
<td>Jean Van Bladel</td>
<td>IEEE</td>
<td>1976</td>
</tr>
<tr>
<td>Computational and Experimental Analysis of Scattering by Rotating Fans</td>
<td>Tardy, Piau, Chabrat, Rouch</td>
<td>IEEE</td>
<td>1996</td>
</tr>
<tr>
<td>Masters Thesis -- Coupling between multiple wire antennas on complex structures</td>
<td>Stavros V. Georgakopoulos</td>
<td>ASU</td>
<td>1998</td>
</tr>
<tr>
<td>Rotor Blade Modulation on Antenna Amplitude Pattern and Polarization: Predictions and Measurements</td>
<td>Birtcher, Balanis, DeCarlo</td>
<td>IEEE</td>
<td>1999</td>
</tr>
<tr>
<td>Rotor Modulation of Helicopter Antenna Characteristics</td>
<td>Polycarpou, Balanis</td>
<td>IEEE</td>
<td>2000</td>
</tr>
<tr>
<td>Title</td>
<td>Author</td>
<td>Publisher</td>
<td>Date</td>
</tr>
<tr>
<td>--------------------------------------------------------------</td>
<td>-------------------------</td>
<td>-----------</td>
<td>-------</td>
</tr>
<tr>
<td>Ka-Band Satcom in A2C2S</td>
<td>Cerasoli</td>
<td>IEEE</td>
<td>2004</td>
</tr>
<tr>
<td>FDTD Modeling of Helicopter Antenna Pattern Rotor Modulation</td>
<td>Birtcher, Balanis</td>
<td>IEEE</td>
<td>2005</td>
</tr>
<tr>
<td>Rotor Modulation Reduction Via Spatial Diversity</td>
<td>Balanis, Birtcher, Yang, Huang</td>
<td>ASU/AHE</td>
<td>2005</td>
</tr>
<tr>
<td>Communication Channel Model with Rotor Modulation Fading</td>
<td>Balanis, Birtcher, Yang, Huang, Kononov, Bevelacqua</td>
<td>ASU/AHE</td>
<td>2006</td>
</tr>
<tr>
<td>Broadband Cosite Analysis of V-22 Airframe using CST Microwave Studio</td>
<td>Willhite</td>
<td>2009 CST</td>
<td>2009</td>
</tr>
<tr>
<td></td>
<td></td>
<td>UGM, Dallas</td>
<td></td>
</tr>
</tbody>
</table>